THE UNIVERSITY OF QUEENSLAND

Bachelor of Engineering Thesis

Correlation of Rock Strength Between Uniaxial Compressive, Brazilian and Point Load Tests: A Laboratory Study

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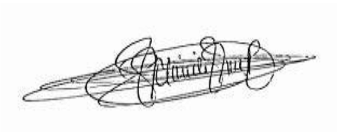
STATEMENT OF ORIGINALITY

I, Claude Ronmar, hereby declare that this report is my own work and that it contains, to the best of my knowledge and belief, no material previously published or written by another person, nor material which, to a substantial extent, has been submitted for another course, except where due acknowledgement is made in the report.



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ABSTRACT

Rock engineering design for underground or on-the-ground projects and operations are widely dependent on different properties of rocks among which strength is one of the main components. The uniaxial compressive strength (UCS) test is still considered to be the most effective method, currently used by many industries to estimate either intact or rock mass strength along with other rock strength empirical indices. The Uniaxial Compressive Strength is the test in which a rock sample of either a prismatic or cylindrical shape is compressed between two parallel rigid plates under a constant strain rate while the load, axial and lateral deformations are recorded by a data acquisition device. However, determining the UCS of rocks is a very complex process due to the need of having quality rock samples, sampling and coring which is time consuming as well as being costly. Furthermore, based on economic reasons, it has never been feasible to get a full measurement of every characteristics and other factors affecting the rock behaviour for UCS purpose. Due to its complexity, studies and researches are still being conducted to ensure cost and time currently involved are minimised by providing some correlations between different other tests which are easy to conduct.

This paper reviews the Brazilian Tensile Strength Test (BTS) and the Point Load Index Test (PLI) established by previous researchers by conducting laboratory experiments and correlate the findings between these two tests and the UCS tests so that they can be used as alternative options on particular specific rock samples. BTS test is performed by compressing a sample between two curved loading jaws as shown in Figure 2 b). Point load on the other hand, is performed manually by compressing a sample between two conical steel platens as shown in Figure 3.

In order to achieve that, a literature review was conducted to understand rock behaviour under the influence of a load and previous findings. In addition to that, three samples (Sandstone, Basalt and Brisbane Tuff) were sampled, cored, and tested using UCS, BTS and PL machines in line with the International Society for Rock Mechanics (ISRM). Previous researches have shown that there is correlation between UCS, BTS and PL with the most commonly used for converting k factor from PL into UCS being (22-24) x $I_{s(50)}$ and a whole range of other conversion factors for UCS and BTS. However, over the past years, throughout the whole previous researches all these factors were found to changing based on rock types and other geological properties in the rocks. Hence, the need to conduct as many experiments as possible on different rock types in the aim of correlating the results by either validating previous findings

or providing new coefficient factor for future use. Due to the general usage of certain conversion factors, this paper focused on these particular three rock samples in order to prove whether the past findings also apply to these them.

For the conversion of the PL into UCS, the k factor was found to be 17.78, 25.78 and 32.62 for Sandstone, Brisbane Tuff and Basalt respectively while the conversion from BTS to UCS, the k factor was found to be 10.55, 10.65 and 15.14 for sandstone, Brisbane Tuff and basalt respectively. It can be seen that from these data, there is no general *k factor* to convert from BTS or PL into UCS and hence the reason why more investigations still need to be done to increase the chance of getting a general *k factor* for different rocks.

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1. INTRODUCTION

1.1 BACKGROUND

Rock strength is one of the main factors which is required in rock engineering design and process. The majority of all underground or on-the-ground projects and operations are widely dependent on different properties of rocks among which strength is one of the main components of rock mechanic design. The most effective method currently used to estimate either intact or rock mass strength is the determination of the uniaxial compressive strength (UCS). Various engineering disciplines such as rock cutting for Tunnel Boring Machine (TBM), rock drilling design and performance, blasting, underground excavations, dams and many more other applications rely on a better understanding of the rock behaviour under the influence of load in intact rock material and any other rock properties found in rock mass in general. Hence, the need to determine the UCS is vital. In order to determine the UCS of rocks, experimental tests are conducted using different method available. However, some of the methods used such as the UCS test are very time consuming, complex and costly due the conditions samples have to be in, the suggested dimensions by the International Society for Rock Mechanics (ISRM), sampling, coring and other physical and geological properties. By taking into consideration all the factors involved in determining the UCS of rocks, many researches are still being conducted to find the easiest way to determine the UCS. To do this, researchers have carried out experiments on different rocks using other methods such as the Brazilian Tensile Strength (BTS) and Point Load (PL) to determine the correlation between either one of those methods and the UCS test (Kahraman *et al*. 2012; Altindag and Guney, 2010). Unlike other engineering materials such as steel where its properties can be assumed based on standard measurements, rock mass properties depend on mineral compositions, arrangement of grains, its history of formation as well as other geological and geotechnical factors (Jaeger, Cook and Zimmerman, 2007). Thus, this project focused on determining the UCS of sandstone, basalt and Brisbane tuff samples and concluded with a specific correlation between these three methods for these particular rocks.

1.2 PROBLEM DEFINITION

The determination of UCS of rocks is still the most common way of determining the strength of intact rock and rock mass regardless of its complexity due to the need of having quality rock samples, sampling and coring being time consuming as well as being costly (Nazir, *et al*. 2013). Understanding the rock strength behaviour under the influence of axial load remains an important tool widely used in the rock mechanics and engineering design. Based on economic reasons, it has never been feasible to get a full measurement of every characteristics and factors affecting the rock behaviour (Bieniawski, 1974). Furthermore, different methods such UCS, BTS and PL have been used to determine rock mass strength of hard or soft rocks (Tumac, 2014; Altindag and Güney, 2006; Karaman and Kesimal, 2014). However, the main focus in previous works was on providing the strength of one rock type and most of the rocks tested were coming from different locations with different rock mass properties. In addition to this, any previous correlations have resulted in different converting factors between UCS and PL or UCS and BTS (Tumac, 2014; Altindag and Güney, 2006; Karaman and Kesimal, 2014) and were never conducted between sandstone, basalt and Brisbane Tuff. Hence, this experimental investigation looked at different samples originated from the same core piece, sampled in the same conditions and use the different methods to generate data which were used to predict the rock strength for all rocks with similar rock mass properties.

1.3 AIMS AND OBJECTIVES

Rock strength plays a big role in rock mechanic engineering and design. It is among one of the parameters which dictates rock cuttability, rock fracturing behaviour and resistance to localised elastoplastic deformation (Boutrid *et al*, 2015). The relationship between parameters of fundamental mechanical tests such as UCS, BTS, and PL on one sample has not yet been amenable. It is therefore important to conduct tests on the same sample using different methods and provide data that can be used to relate each rock strength test method to another.

The aim of this project is to experimentally investigate rock strength by using different testing methods such as UCS, BTS, and PL tests on three samples. In addition to that, the results obtained from the experiment are used to determine the correlation between the three different tests by providing the conversion factors which specifically apply to these three rock types.

To achieve the aim of this experimental investigation, the following was implemented:

- conduct a concise literature review to be able to understand the previous work done for these particular tests as well as understanding the properties of the rocks for the experiment;

- determine other possible existing relationship between methods used to determine the strength of different rocks;

- conduct rock fundamental mechanical tests using UCS, BTS and PL machines for rock strength using the three rock samples as mentioned above; and
- analyse and interpret parameters resulted from the investigation to determine the relationship between the UCS of different rocks and the other two methods (PL and BTS).

1.4 PROJECT SCOPE

Initial activities were conducted throughout the whole research process to ensure that the project credibility is maintained. However, a number of other activities need to be done in the future or otherwise they would not fit within the scope of the project. The scope of the project is shown in Table 1.

Table 1

Scope of the project.

In scope	*Out of scope*
Sample coring	Extensive numerical modelling and simulations
Literature review on past research	Hydrostatic tests
Uniaxial Loading on samples	Poroelasticity and thermoelectricity tests
Collection of data	Triaxial Loading on samples
Conduct UCS, BTS and PL tests	Conduct tests on samples with different temperatures
Calculation of rock strength	
Determine the correlation between the 3 tests	

1.5 ASSUMPTIONS

The assumptions made in this project were:

- loading on specimens is uniform;
- the specimens are isotropic;
- the Brisbane Tuff, Basalt and Sandstone have been prepared in the normal standards and conditions as stipulated by ISRM;

- all the samples are homogeneous;
- as the samples will be cut out of one big core piece, it assumed that they will all have the same geological and geotechnical characteristics;
- there will be no initial defects; and
- samples are dried at room temperature.

1.6 RELEVANCE TO INDUSTRIES

In rock mechanic engineering, rock mass strength, is one of the key factors that is considered to be used the most when it comes to designing the rock cutting performance equipment, mining method design in both underground and open cut. The most commonly used way to determine the rock strength is the use of UCS test. However, the time, cost and restriction on the type of machines used for this method is not flexible. Hence other cheaper methods such as PL and BTS tests are used (Sheshde and Cheshomi, 2015; Swain, 2010). The outcome of this research would serve as a primarily reference to different rock engineering design. Rock sample preparations are very time consuming and sometimes expensive that estimations are tending to be the easiest way to conduct experimental (Altindag and Guney, 2005). Thus, the outcome of this project is set to reduce the cost and the time used to prepare the samples, to conduct the tests in order to determine the UCS under the current standards. The applications of the findings for this experiment are important to a number of industries such as in mining, rock excavation, rock engineering design, rock cuttability and the reduction of time and cost associated with rock UCS determinations.

Furthermore, due to the fact that the project is a laboratory study, the data collected will be able to determine a correlation between rock strength which is only specific to these three samples used in the experiment. In addition to that, the results in this project are likely to benefit a lot of industries in predicting the ability to cut rocks for the Tunnel Boring Machine (TBM) and fracturing behaviour. Furthermore, it should be noted that UCS and UTS play a key role in the underground design for roof and cut through stability especially when dealing with soft rock. The experimental results and the outcome of this study can improve the understanding of rock fracturing behaviour for oil reservoirs and hydrothermal energy resources.

2. LITERATURE REVIEW

2.1 BACKGROUND

A literature review is considered as the first step for a successful experimental investigation. This consists of searching for information related to the experiment to be conducted so that there is an insight and thorough understanding of what the investigation is about. It involves finding related information from available journals, papers, books, web sites, reports and theses. Furthermore, a literature review helps to relate the work which has been done by other fellow researchers in the aim of improving or using information as reference. Rock behaviour and properties are so complex that an understanding and an analysis is needed to be aware of what to expect from the rocks during the test. Once enough literature review has been assimilated, then follows the experiment whereby, samples are made ready, get them experimentally tested and analyse the results for final findings. However, all the past findings might not always reflect to the intended results of the project and might be lacking some important information. Hence they have to be critically reviewed and improved where possible.

2.2 PREVIOUS STUDIES

2.2.1 Background

Several researches have been conducted so far in relation to the determination of UCS of rock mass strength by conducting either direct or indirect strength tests. Due to the complexity of the whole procedure of UCS determination in different rocks from coring samples to conducting experimental tests, studies and researches are still being conducted to ensure cost and time currently involved are minimised by providing some correlations between other different tests for a number of rocks. Furthermore, other factors affect considerably the excavation of rocks which leads to practically impossible to determine all the rock mass attributes. This affects the ability to predict the rock strength and the impact of those rock attributes on determining the UCS (Bieniawski, 1974). In this thesis, UCS, BTS and PL are looked at individually and the results are used to determine the correlation between them using the formula and application developed by previous researchers.

2.2.2 Correlation between UCS and BTS

The correlation between the UCS and the BTS has been around for a very long time. One of the most commonly used correlation is part of the study done by Sheorey in 1997 as cited in Nazir et al. (2013). In that study, UCS was found to be 10 times its tensile strength. However, this finding does not specify the number of tests conducted to verify the reliability of the results. In addition to that, the types of rocks used in this experiment were not specified. According to Cai (2016), the study by Sheorey showed that the strength ratio was found to be high and therefore, the 10 times factor of correlation should not be used as general standardised *k factor* given the fact that rock behaviour varies from one place to another. In another study conducted by Kahraman et al. (2012), their results showed that there is a linear correlation between UCS and BTS. The *k factor* was found to be 10.61 times the BTS test. However, the coefficient of determination R^2 was only 0.5 which is not reliable enough. Physical properties and other geological factors affect how the rock behaves. Hence, Altindag and Guney (2010) conducted a research for a wide range of strength values and found out that for the same rock types, the UCS ranged from 5.7 to 464 MPa whereas their corresponding BTS values ranged between 0.5 to 30.5 MPa. However, these ranges are wide spread to be incorporated in the actual converting factors. Other correlations between UCS and BTS can be found in the experiment conducted by Jaeger, Cook and Zimmerman (2007) and Erarslan, Liang and Williams (2011) on limestone and these correlations can be found in Appendix A, Table 25. It should be noted that these data are not used as of part of the findings for this thesis. Furthermore, the variation in the values obtained previously proves the need to conduct the test on specific samples for the *k factor* to be determined. Table 2 shows a summary of some of those recent correlation.

Table 2

Recent correlation between UCS and BTS.

References	*Correlation*	*R^2*	*Rock type*
Kahraman *et al* (2012)	UCS (Mpa): 10.61*BTS	0.5	Different rock type including limestone
Farah (2011)	UCS (psi): 5.11*BTS-133.86	0.68	Weathered Limestone
Altindag and Guney (2010)	UCS (Mpa): 12.38*$BTS^{1.0725}$	0.89	Different rock types including limestone

2.2.3 Correlation between UCS and Point Load Tests

Although the UCS is still considered the common way to determine the strength of the rock, a number of other factors under which the test is conducted are leading to researchers trying to seek other alternatives to obtain the same rock strength. So far point load test has been chosen by many researchers to be the easiest method for the rock strength determination (Singh *et al*, 2012; Chau and Wong, 1996; Li and Wong, 2012). PL is cheaper, easy to use and simple when it comes to specimen preparation (Li and Wong, 2012). Based on some experiments conducted on different types of rocks such as igneous, metamorphic and sedimentary rocks, it was found that although there is a trend in determining the conversion factors between UCS and PL, it varies between rock types and classes (Rusnak and Mark, 2000; Kahraman, Fener, & Kozman, 2012; Kahraman *et al*, 2005).

Due to the fact that the results are from different rock types, it is still hard to determine the standard converting factor. The early stage of the correlation between the UCS and PL showed that the k factor as the conversion factor was 24 (Bieniawski, 1974). Later on, another accepted regression equation was experimentally determined to predict the compressive strength and experimental studies were conducted on rocks from India. The recommended conversion factor was 21 to 24 for hard rocks and 14 to 16 for soft rocks (Singh *et al*, 2012; Chau and Wong, 1996).

3. RISK ASSESSMENT

The majority of work for this project was conducted in different laboratories and the locations at The University of Queensland. Due to the amount of work and the environment the work was carried out, a risk assessment had to be done prior to any commencement of the experiment as well as during the progress of the thesis. This determined all potential hazards to harm an item or individual and their mitigation from the start to the end. The World Health Organisation (WHO) and the University of Wollongong (UOW) (2009), define risk assessment as a scientifically based process which is done using few steps which are elaborated in a way that it responds to a number of questions such as why is it needed, when is it to be done and what to do next. Furthermore, it involves the identification of hazard, characterisation of the hazards, and what are the mitigating measures to be done to be able to minimize the risks and hazards associated with the investigation (UOW, 2009). For this particular projects, the risks are not only related to harm which can occur over the period of work but also the risks which can prevent the completion of the project on the due date. Figure 1 illustrates the steps to follow when conducting the risk assessment, once hazards have been identified, and all the parameters have been defined, it is possible to use them and indicate the potential risks, how more likely they will occur a number of controls, preventive methods and mitigation can be elaborated. These controls vary depending on the type of the hazards encountered. Sections 5.1 and 5.2 shows the risks and hazards associated with the experiment and those which can affect the completion of the project respectively.

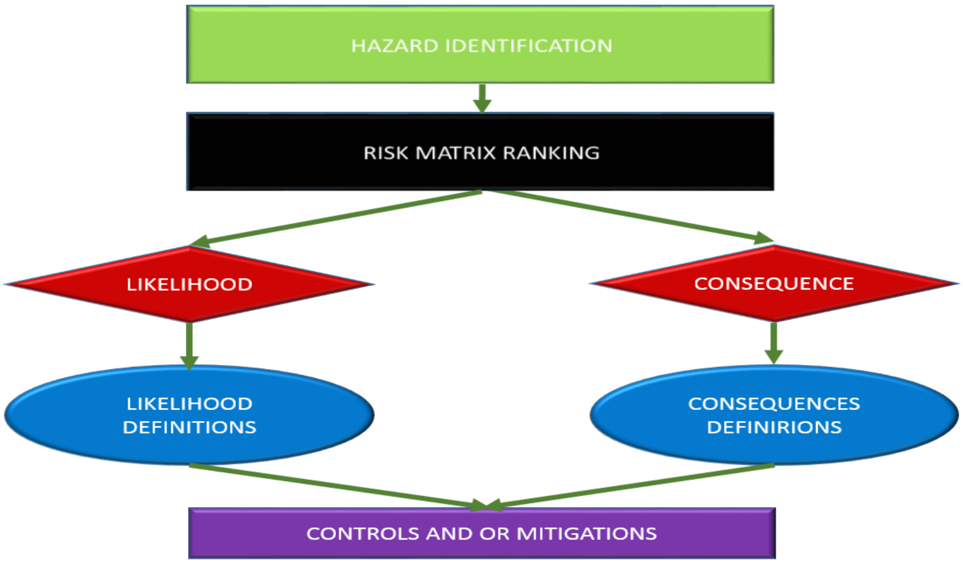


Figure 1. Hierarchic Steps for risk assessment investigation.

As mentioned above, some risks are associated with conducting the experiment and other risks are associated with the whole project. That is risks whose factors will affect the completion or achievement of the aims and objectives of the project. Table 3 shows how the risk ranking method is used based on the likelihood and the consequence associated with it. To find the risk ranking matrix the following formula is used.

$$Risk\ Ranking\ Matrix = Likelihood\ x\ Consequence$$

Based on that formula the highest rank is 25 as it can be seen in Table 3. Hazard can have a high chance of happening but if its impact is negligent it will have a low ranking. Hence, controls will still be implemented to avoid any unforeseen consequences or reduce the likelihood.

Table 3

Ranking strategies based on the consequences and the likelihood of the hazard.

LIKELIHOOD	**RISK RANKING MATRIX**				
HIGH	**5**	**10**	**15**	**20**	**25**
SIGNIFICANT	**4**	**8**	**12**	**16**	**20**
MODERATE	**3**	**6**	**6**	**12**	**15**
LOW	**2**	**4**	**6**	**8**	**10**
NEGLIGIBLE	**1**	**2**	**3**	**4**	**5**
CONSEQUENCE	**NEGLIGIBLE**	**LOW**	**MODERATE**	**MAJOR**	**CATASTROPHIC**

The likelihood needs some description to be able to reflect to the proper meaning of what low to high means when evaluating these hazards and risks. Hence, Table 4 outline what their corresponding descriptions are.

Table 4

Description of the probability of occurrence for any hazard.

Likelihood Definitions	
A **High** Likelihood	This is expected to happen most of the circumstances The probability of reoccurring is high
A **Significant** Likelihood	Hazards of the same aspects have been recorded often This type of hazards is likely to occur again
A **Moderate** Likelihood	Incidents and hazards of this type have occurred frequently regularly but in the past.
A **Low** Likelihood	There have only been few known incidents of this type to occur This has not happed yet but its occurrence cannot be ruled out.

A **Negligible** Likelihood	This type of incident has never occurred before It would have to be exceptional to occur

The consequence related to the occurrence of accident due to unforeseen risks or hazards need to be defined. This can help pick up the severity of certain risks which can help to prevent them.

Table 5

Description of the different types of consequences to be encounter.

Consequence Definitions	
Catastrophic	Result in single and or multiple death Very costly (Estimated up to $5million Everyone nationally and worldwide is talking about it
Major	Result in serious health impacts on multiple or single persons and permanent disability. Costly. Estimated between $2.5 – $5 million National media outrage
Moderate	Result in people being injured and the sustained injuries would require more than 10 days rehabilitation Costly. Estimated between $200,000 and $2.5 million Local media and community concern
Low	People are injured and this can result in losing time and claims Cost estimated between $50,000 and $200,000 Minor isolated concerns raised by stakeholders, customers
Negligible	Minor injury to people. Only first aid required Cost estimated up to $50,000 No much of impact to reputation

Table 3, 4 and 5 illustrates the methods to differentiate one event from another in terms of the rating, likelihood and consequence. These definitions have been used by different companies or people (WHO, 2009; UOW, 2009).

3.1 Risks and Hazards Associated with Experiment

Risks and hazards are classified in different categories. Some are mainly affecting the project completion or development while others are only associated with the experiment. Table 6 gives a full description of some of the risks and hazards to expect during the experiment.

Table 6

Risks and hazards associated with the Experiment.

Activities	*Hazards*	*Likelihood*	*Consequence*	*Rating*	*Controls*
Handling of samples	Breakage,	3	1	3	Handle them with cautions
	Loosing Samples	1	1	1	Find a container where they all put together all the time
	Dropping Samples on Feet	1	1	1	Handle them carefully, always ware PPE
	Inhaling Dust	3	1	3	Wear dust mask
Laboratory Equipment and handling	Lack of water	1	5	5	Check if the lab has water tub before commencing work. Always carry a spare bottle for later use.
	Cable, Electrocution	2	5	10	Always check on all the power points, Use protective gloves
	Ventilation	1	5	5	Prepare to equip with spare fans in this conditions
	Untidy (Dust for self-ignition combustibles	1	5	5	Keep the laboratory tidy
	Fire	2	5	10	Always check on things which can start fire, voltage of equipment, have a working fire extinguisher
	Flammable	2	5	10	Avoid to use flammable equipment and stay away from potential igniters
	Calibration	1	3	3	Always check on equipment's calibration for accurate results

	Injury from moving equipment	2	3	6	Use current technique and for heavy ones, seek help to lift them together
Sample Preparation	Breakage	3	1	3	Handle them with cautions
	Wrong Dimensions	2	3	6	Always on specifications and standards for samples. If not sure research or ask the supervisor
	Cut/injury from tool usage	2	3	6	First aid bandage handy, use them with cautions
	Dropping on feet	2	3	6	Carry them carefully, Wear essential PPE
	Dust inhalation	3	1	3	Wear Mask
Conducting Experiment	Unexpected Rock fracturing	2	2	4	Make sure equipment are equipped with glass to protect. If not, wear safety glass and keep away
	Power outrage	2	1	2	Stop work and wait until fixed
	Lack of enough samples	2	3	6	
Data manipulation after experiment	Human Errors: Misinterpretation, results or calculation	2	3	6	Take extra precaution in handling and manipulating. Check with supervisor
	Data collection Data Loss (Storage damaged)	2	3	6	Always have a back plan such as saving on different storage

3.2 RISKS AND HAZARDS AFFECTING THE COMPLETION OF THE PROJECT

The risks and hazards can also affect the project other than the equipment or individuals. Hence, a back-up plan on risks and hazards which are more likely to affect the project were looked at. Table 7 shows a full description.

Table 7

Risks and Hazards affecting the completion of the project.

Hazards	*Likelihood*	*Consequence*	*Rate*	*Controls*
Sample delays	2	3	6	Set date for Delivery. Organised preparation at early stage. If prepared outside, arrange delivery
Not enough sample	2	3	6	Start with some and increase the samples as the experiment goes. Check with the supervisor.
Not enough collected data	1	3	3	Repeat the process for the extra sample until the target is reached
Loss of Data Storage (Computer, USB)	2	5	10	Have spare storage and back up hard drive and save the project on different storage
Misinterpretation of Supervisor's comment	1	1	1	Consult the supervisor on regular basis and request more clarifications
Misinterpreting Data	2	2	4	Do more research as to what to expect. Check with the supervisor for clearance
Poor time management	2	2	4	Start working on the project as soon as possible. Set up goals to be

				achieved every week
Insufficiency of resources and reference	2	2	4	Allow plenty of times to research and talk to the supervisor for suggestion
Project objectives are not clear	2	2	4	Engage in regular consultation with the supervisor and request more clarifications
Injury and Sickness for the researcher	1	3	3	See the doctor for treatment as soon as possible and come back after.

3.3 Contingency Plan

Some of the hazards and risks maybe inevitable to occur but they can be controlled once they have happened. A contingency plan is implemented to make sure that the identified risks and hazards are weighed and controlled once controls in place fail. Thus, Table 8 shows the full description.

Table 8

Contingency Plan.

Hazard	*Rated Risk*	*Control Plan*
Cable, Electrocution	High	Always have emergency phone number handy. Exit plan.
Power outrage	Moderate	Have another power generator to use after.
Loss of Data Storage (Computer, USB)	High	Have a backup plan. Use two documents. Save them Separately with one allowing online access and keep saving them at all time.
Poor time management	Moderate	Have some days working beyond schedule to cover the unproductive days

Injury and Sickness for the researcher	High

3.4 METHODOLOGY

Any method used for this experiment requires enough and a better understanding of the topic and the types of tests to be conducted. In order to achieve that, a literature review was done to ensure that questions like how, when and why are studied and answered for the topic. The mechanical properties of rock mass depend on a number of various factors. Unlike other engineering materials such as steel whereby its properties can be assumed based on standard measurement, rock mass properties depend on mineral compositions, arrangement of grains, its history of formation as well as other geological and geotechnical factors (Jaeger, Cook and Zimmerman, 2007). Hence, the tests are done on prepared rock samples with rock mechanic properties which have been roughly estimated by using the ISRM and the American Society for Testing Materials (ASTM) standards. When conducting an experimental investigation on rock strength, it is noted that the type of instrument used in the test as well as the procedure used affect the results which is why mechanical properties such as strength and rock failure are not considered as inherent material properties (Goktan and Gunes, 2005). Although field and laboratory tests are the two types which can be conducted for rock strength tests, this thesis only focused on laboratory testing.

3.4.1 Sampling

Sampling is an important part of the experiment as it plays a key role on the rock properties of the specimens. The sample has to follow the ISRM standards to be valid. This includes measuring the dimensions, determine the shape and the consideration of the grains and other rock properties prior to testing such as moisture content and in-situ conditions. The samples used for this thesis, are all in a dry condition at a room temperature. In order to determine the UCS of the rocks, all the geological, physical and mechanical properties have to be specified for the purpose of any design involving rocks. To do that, the rock samples had to be kept and handled in such way that nothing is altered.

3.4.2 Sample Preparation

The preparation of samples is one of the major issues before conducting any experiment as they have to be prepared according to the ISRM standards and less probably to the ASTM standards. In addition to that, all the samples were coded to make sure each samples results are not mixed and reflect to the properties of that particular samples. Dinc *et al* (2011) and Altindag and Güney (2006) discussed how hard it is to prepare the representative core of rock masses containing discontinuities for any laboratory studies, as it requires more time, money and precise dimensions especially when they are weathered. Hence, a long core rock of each type was prepared and subdivided into standardised samples as specified in the ISRM and ASTM standards to maintain the same rock mass properties, geological and geotechnical features. The main objective of using subdivided samples from one same core is to avoid any induced damage inter-testing such as internal fracturing and maintain the geological and geographical characteristics as well as adhering to the standards in order to make sure that the results obtained are consistent and valid for analysis purpose. As mentioned before, in this research, Brisbane Tuff, Basalt and Sandstone were chosen to undergo UCS, BTS and PL tests. Each sample was used and chosen after a thorough analysis of the other types which have been used for the same purpose as suggested in the past findings.

3.4.3 Storage

The samples used in this experiment were kept in one place under reasonable conditions to ensure that they are suitable for laboratory testing. Samples that are not stored in good conditions may be affected by the moisture content and atmospheric gas which can mislead the results.

3.4.4 Transportation

As usual, samples were transported in trucks. In order to avoid interaction with the external atmosphere, they were kept in wooden boxes which protected them from the sunlight. Furthermore, it should be noted that rainfall can affect the laboratory testing if samples are not protected properly during transportation.

3.4.5 Laboratory Testing

The laboratory used for this research was at The University of Queensland in the Advanced Engineering Building (AEB). For UCS and BTS, one testing machine was used. The only difference between the two tests was the configuration on how the samples were placed in the machine. The equipment used for both UCS and BTS was the INSTRON 5000R 4505 as described in Figure 2

a) UCS Test

b) BTS Test

Figure 2. Instron Equipment for UCS in a) and BTS in b)

As it can be seen in Figure 2, the sample for UCS test was compressed between two parallel rigid plates. The axial deformation and the peak load were recorded using a data acquisition connected to the Instron machine. The loading rate was set at 0.8kN/s. This loading is also accepted by the ISRM. For the BTS test, the configuration set up was that the sample was compressed between two curved loading jaws as the figure shows in b). It should be noted that the loading was also 0.8kN/s to maintain consistency and was a diametrical loading.

As stated previously, the third test conducted was the point load test and this was done by a different machine. Figure 3 shows the set up for the PL test. The sample in this case was compressed between two conical steel platens and the experiment was performed manually with information of the peak strength displayed on the machine.

Figure 3. Point Load Test Machine.

4. EXPERIMENTAL PROCEDURE

4.1 UNIAXIAL COMPRESSIVE STRENGTH TEST

4.1.1 Overview

The Uniaxial Compressive Strength is the test in which a rock sample of either a prismatic or cylindrical shape is compressed between two parallel rigid plates under a constant strain rate while the load, axial and lateral deformations are recorded (Hawkes[1] and Mellor[2], 1969). This is considered as the oldest method but simple and it is still widely used. Furthermore, the determination of the UCS can be done by direct or indirect strength tests (Jaeger, Cook and Zimmerman, 2007). The determination of rock UCS is an important tool which serves as a defining factor of the rock geotechnical properties. It is seen widely used in engineering sectors such as mining, civil structural and infrastructure (Sheshde and Cheshomi, 2015; Szwedzicki, 1998). The usage of UCS test on sample aims at finding the Young's Modulus, E, as well as the UCS value. In general, the UCS in rocks varies and the variation depends on geological factors, geographic locations, porosity, density and ages (Cheshomi, Mousavi and Ahmadi-Sheshde, 2015).

4.1.2 UCS Testing Standard

The UCS parameters need accuracy and need to be standardised according to the ISRM specifications. Table 9 illustrates suggested parameters used to conduct a UCS test (Erarslan, 2014). However, the ASTM recommends that the ratio Length over Diameter (L/D) of 2 to 2.5 generates good results. In contrast, researches have shown the variation in value of UCS based on the ratio used. It was analysed that high UCS values are obtained when sample have the ratio L/D of less than 2, a bit different when the ratio is between 2 and 2.5 and are constant for L/D ratio greater than 2.5:1(Tuncay and Hasancebi, 2009). Hence for consistency, ISRM standards was used in all the samples accordingly. Where the dimensions are slightly different to the ISRM standards, the equivalent diameter was used to make sure the ratio L/D complies with the ISRM.

Table 9

Suggested Parameters to conduct the UCS Tests.

Diameter (mm)	*L/D Ratio*	*Ends Perpendicular to (mm)*	*Loading Rate (MPa/s)*
≥ 54	2.5 to3	0.02	0.5 to 1

4.1.3 UCS Testing Procedure

As described previously in this thesis, UCS is used to determine the strength of the rock by applying a compressive stress on a cylindrical core between two parallel rigid metal plates as described in the book by of Jaeger, Cook and Zimmerman (2007), Chapter 6. The hydraulic fluid pressure is then used for the application of the load. This procedure is intended to make sure only the uniaxial stress is induced as per the following equation:

$$\tau_{zz} = \sigma,\ \tau_{xx} = \tau_{yy} = \tau_{xy} = \tau_{yz} = \tau_{xz} = 0 \qquad 1)$$

This means that only the axial load is applied to the rock sample and no other type of any form is applied. Hence, $\sigma_1 > 0, \sigma_2 = \sigma_3 = o$ (Shanableh, Omar and Salah, 2014). There is a range of different ways to determine the unconfined compressive strength and Young's Modulus (Jaeger, Cook and Zimmerman, 2007). One way to calculate the longitudinal strain is by using a strain gauge which is attached on the lateral specimen surface. Otherwise a shortening of the core in the same direction as the loading can be measured using an extensometer. The Young's Modulus (E) is a function of stress (σ) and strain(ε).

$$E = \frac{Stress}{Strain} = \frac{\frac{F}{A}}{\frac{\Delta L}{L}} = \frac{\sigma}{\varepsilon} \qquad 2)$$

where:

E: Young's Modulus (GPa)

F: applied force (kN)

A: cross sectional area (m^2)

L: length (m)

$\sigma = \frac{\mathrm{F}}{\mathrm{A}}$ (MPa)

$\varepsilon = \frac{\Delta L}{L}$

UCS tests are mainly resulting in permanent deformation as they tend to determine the maximum strength of the specimen before failure. Figure 4 shows different configurations which can be adopted during UCS experiment. As it can be seen, UCS test is done vertically rather than diametrically on the samples. Each configuration has an impact on the results that can be obtained. However, this thesis only focussed on configuration (a). All the fractures observed during the experiment were in the form of configuration in (a) and the photos can be found in Appendix B

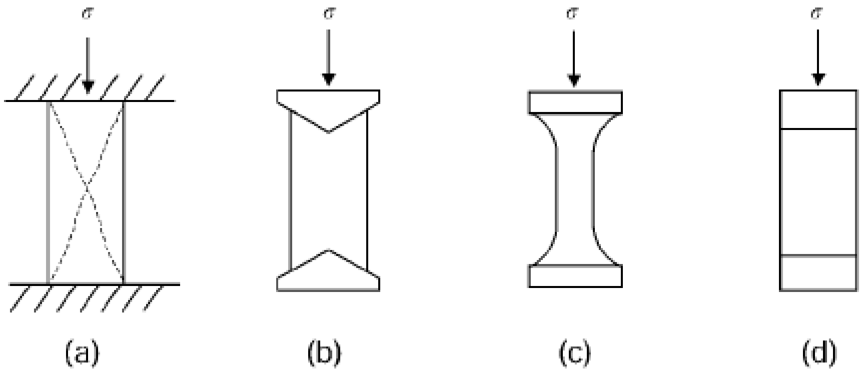


Figure 4. Different configurations of UCS Test

4.1.4 Advantages and limitations of UCS Test

The Uniaxial Compressive Strength is known to be the most fundamental measurement which can be using in a number of discipline but more importantly in geotechnical rock and in mine design. Hence, the determination of the UCS presents a huge advantage in industries which are in direct contact with rocks. Another advantage is that once the UCS has been determined, the value is better known, evaluated and can be available for a wide range of other rock types (Bieniawski, Z T, 1974).

UCS test has got a whole range of limitations and for this reason, indirect UCS estimation using other simpler methods is employed. UCS is strictly adhering to standard methods, time consuming and expensive (Sheshde and Cheshomi, 2015; Szwedzicki, 1998). Furthermore, it is hardly possible to find standard core samples in some conditions such as oil and gas well drilling (Sheshde and Cheshomi, 2015). Furthermore, some rock types fail before the UCS test is performed due to their related structures and geometric parameters which aren't adhering to the standards (Shanableh, Omar and Salah, 2014). While conducting the experiment, it is pointed out that stress results from the test may not be homogenous due to displacement in the sample and would have implication on young's modulus and compressive strength. Hence, boundaries should be applied to limit the displacement and improve the outcome.

4.2 BRAZILIAN TENSILE STRENGTH TEST

4.2.1 Overview

The Brazilian Tensile Strength method was developed by the Brazilian Engineer Fernando Carneiro back in the 1943 (Jaeger, Cook and Zimmerman, 2007). The main reason of the Brazilian Tensile Strength test is to measure the tensile strength of rocks and other materials. In addition to that, it has been stipulated that most rocks in biaxial stress fields are more likely to fail in tension due to the fact that the principal stresses are tensile and compressive respectively (Andreev, 1991; Li and Wong, 2013). Rocks behave differently when in tension compared to their behaviour when in compression or shear and this is sometimes neglected in some applications such as engineering practice (Hsu and Chen, 2001). However, these tests are crucial especially when it comes to cutting, blasting and blasting horizontally bedded roof strata. Hence, the interest in conducting this test in this thesis. In addition to that, this test is easier to conduct and hence the values from this test would be used to relate with the UCS values and determine the correlation for future reference on these types of rocks.

4.2.2 BTS Test Standard

The parameters which are used for BTS test are standardised as specified by the ISRM. This thesis may adopt but not limited to the dimensions found in the experiment done on the Brisbane tuff. These parameters are found in the experiment conducted by Erarslan, Liang and Williams (2011) in reference to the ISRM standards. Table 10 shows some of the parameters used for the Brisbane tuff. Figure 5 shows, that there are 4 different range of configurations to be used and the loading arcs used range from 15^0 to 30^0 for the Brazilian jaws (Erarslan, Liang and Williams, 2011). It is noted that the Brazilian jaws configuration can result in a catastrophic failure during experiment whereby crushing failure can occur at any time.

Table 10

Test Parameters as suggested by ISRM (2007).

Diameter (mm)	*Thickness (mm)*	*D/t Ratio*	*Loading Rate (N/s)*
52	26	2	200

4.2.3 BTS Testing Procedure

The Brazilian Tensile Test also sometimes called splitting tension test due to its expected fracturing results is conducted by applying a concentrated compressive load across the diameter of a disc specimen (Erarslan, Liang and Williams, 2011; Li, and Wong, 2013). There are various ways of loading configurations which can be adopted when conducting the experiment and these configurations can be found in Figure 5. It is assumed that the loading on the specimen is uniform and applied at each end of the diameter. The scale of the sample sizes is very small and hence, they can be considered homogeneous. The fracture initiation and propagation is also assumed to be from an intact rock. The stress states considered in this experiment are that they are in two dimensions. Hence, the immediate principal stress is assumed to have no influence on the fracture of the disc (Hoek[a] and Martin[b] 2014; Li, and Wong, 2013).

The four configurations have an impact on how to calculate the tensile strength based on the fact that the disc specimen are loaded under different conditions. To determine a tensile strength of a rock under the Brazilian Test, it is necessary to understand that there is a fracture initiation which happens when the load is being applied on the specimen. Researches have been conducted and it was found that the maximum of fracture initiation happens near where the maximum stress and strain are applied (Li, and Wong, 2013; Erarslan, Liang and Williams, 2011). In this thesis, the configuration used for the BTS test was the one shown in Figure 5 (d). The tensile strength of a rock sample σ_t is calculated by using the following formula (Erarslan, Liang and Williams, 2011):

$$\boldsymbol{\sigma_t = \frac{2P}{\pi d t}} \qquad 3)$$

where:

P: load at failure (N)

d: diameter (mm)

t: the thickness measured at centre (mm).

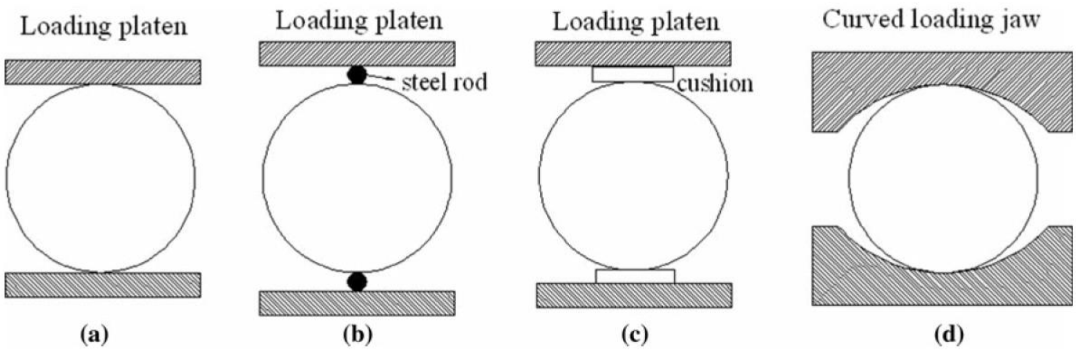


Figure 5. Typical Brazilian tensile test loading configurations (Li and Wong, 2013).

4.2.4 Assumptions

Assumption made for this particular test are as follows:

- applied load were assumed to be applied through the contact point transfer condition and thus the arc contact between sample and platens was dismissed;
- samples are considered homogeneous and isotropic;
- load is uniform and radially applied over the circumference of the sample;
- no friction stress between the platens and the sample;
- the intermediate principal stress (σ_2) is negligible or has no effect during fracturing; and
- the fracture is to initiate in the diametrical line where the compressive stress is applied to be valid.

4.2.5 Advantages and Limitations of BTS test

The BTS is found to be reliable, easy, faster and not costly unlike other difficult methods such as direct uniaxial tensile strength. Research has proven that rocks are much weaker in tension than in compression or shear (Chen and Hsu, 2001). This can be observed in some of the values obtained in this thesis while conducting BTS compared to UCS. This method has been found to be linked to the UCS value in a way that the results obtained by Nazir et al. (2013), showed a correlation ranging from 0.5-0.89. Many other researchers have proven that BTS can be an alternative to UCS which is another advantage to minimise the time, cost and constraint associate with UCS. If prior experiment precautions are not taken such as using steel loading arcs with different angles, the results can be catastrophic whereby the sample is suddenly fractured in a way other than the expected tensile splitting failure which in the majority of the times is initiated by a crack in the very centre of the loading contact (Erarslan, Liang and Williams, 2011). Another limitation is that sometimes the tensile strength is neglected in engineering practice whereby for numerical analysis zero tensile strength is considered to make the calculation convenient (Chen and Hsu, 2001).

4.3 POINT LOAD TEST

4.3.1 Overview

The point load test is referred to one in which sample is held in two conical steel platens and the fracture is initiated at the point of contact due to induced tension which result in a more consistent failure mode (Brady and Brown, 2006). The Point Load Test is also design to determine the rock strength. By using this method, the point load index is calculated from the data obtained during the experiment. Point load test doesn't require sophisticated consideration such as those in UCS test. It is considered to be used when almost all other type can't be performed making it the most reliable method in determining the rock strength (Shanableh, Omar and Salah, 2014).

4.3.2 PL Testing Procedure

As it has been discussed before, point load test is considered as an alternative cheaper method to determine the UCS. The procedure involves the use of conical steel platens in which samples are compressed until the failure has occurred (Rusnak and Mark, 2000). The peak load and the time can be recorded via data acquisition depending on the type of the point load machine used. In addition to the two-point load platens, the apparatus also consists of rigid frame and a hydraulic ram with pressure gauge. The calculation of the point load index is used to determine the UCS by using the conversion factor as previously suggested by other researchers and the ISRM. The ISRM (1985) suggested that the conversion factor between the UCS and PLI ranges from 20 to 25. However, other researchers have demonstrated that the conversion factor vary depending on the rock structure, rock types, and the physical and geological properties (Liang *et al*, 2015; Rusnak and Mark, 2000; Li and Wong, 2012). The point load index is calculated using the accepted ISRM (1985) and ASTM (2008) standards:

$$I_{S(50)} = F \times I_s = \left(\frac{D_e}{50}\right)^{0.45} \times \frac{P}{D_e^2} \qquad 4)$$

where:

F: The correction factor.

I_s: Uncorrelated Point Load Index (MPa)

D_e: Equivalent Diameter (mm)

P: Failure Load (N)

According to Li and Wong (2012), from Equation 4, the correction factor $F = \left(\frac{D_e}{50}\right)^{0.45}$ while the uncorrelated point load index $I_s = \frac{P}{D_e^2}$. The equivalent diameter D_e is mainly depending on the type of load test conducted. Hence the $D_e^2 = D^2$ if the test is diametrical. The calculation of D_e^2 is given by $\frac{4A}{\pi}$ when the test is axial, and any other form other than diametrical. And as for the cross section A in the calculation of the D_e^2 is given by the cross section which pass through the patens in contact with the sample. Thus $A = W \times D$.

4.3.3 Advantages and Limitations of PL test

It is not always possible to find facilities whereby the required standards to prepare the specimens for a UCS test are met. Sometimes the properties of the rock for the UCS test are not specified or do not need to be with only the peak load to failure is required. During these situations, point load is found to be useful (Brady and Brown, 2006). The point load is widely used to determine the UCS of rock strength due to its simplicity, usefulness and cheap procedure. Point load is considered to be easier to use because samples can vary in shapes from cylindrical to other shapes and still be tested. The load can be applied either axially or diametrically (Li and Wong, 2012).

There have been few limitations associated with the use of point load test. One limitation is that soft rocks that are anisotropic with bedding planes, can give wrong results when point load test is conducted. Hence special caution is to taken especially in terms of the consistency in loading rate. Another limitation is only based on the technicality and validity of the test whereby the fracture has to be initiated between 10 and 60 seconds (ISRM, 1985). A general limitation is that the point load test is manually monitored in regards to some data recording which can be wrong especially the loading rate which may vary on every test.

5. PROJECT SCHEDULE

5.1 INTRODUCTION

A project management is considered as the application of all knowledge, skills, tools and technique to the project activities in order to comply with all required tasks for the project (Project Management Institute, 2000). Being able to start, planning and execute make part of a successful project management. Making a project a success is not a simple task. The projection of how any project will be started and finalised faces a number of difficulties and these factors can affect the schedule considerably if no control measures are taken:

- delays;
- inadequate or inaccurate results;
- risks and hazards;
- lack of enough samples for an experimental project;
- loss of data; and
- multiple tasks needed to be completed in the same time frame.

To ensure all the above-mentioned are avoided and that time and resources are wisely managed with effectiveness in the aim of achieving the aims and the goals of the project for the scheduled time, it is important to elaborate a schedule showing all the activities and events of how key tasks will be performed and when the project is intended to be completed has to be outlined. This can be found in Figure 1.

5.2 KEY TASKS

In order to complete this project, two categories of tasks were implemented. The first category includes those tasks which have already been completed while the other category includes those which would be completed in the future.

5.2.1 Completed Tasks

- literature review for the whole project has been done;
- research proposal detailing the aims and objectives has been done;

- data sampling;
- laboratory experiment; and
- compile and analyse the findings for the final thesis.

5.2.2 Future Work

- AusIMM conference Proceeding paper; and
- publication of the paper.

5.2.3 Resources and Costing

This thesis was conducted as part of the university undergraduate program's requirement and therefore the total cost involved in it was dealt by The University of Queensland in the department of Mechanical and Mining Engineering. The covered cost includes:

- coring rock mass;
- delivery of samples;
- preparation of the samples based on the ISRM suggested standards to be used in the experiment at the JKMRC Centre; and
- hiring laboratories and equipment.

Table 5 shows an estimate breakdown of some of the price units involved in the project

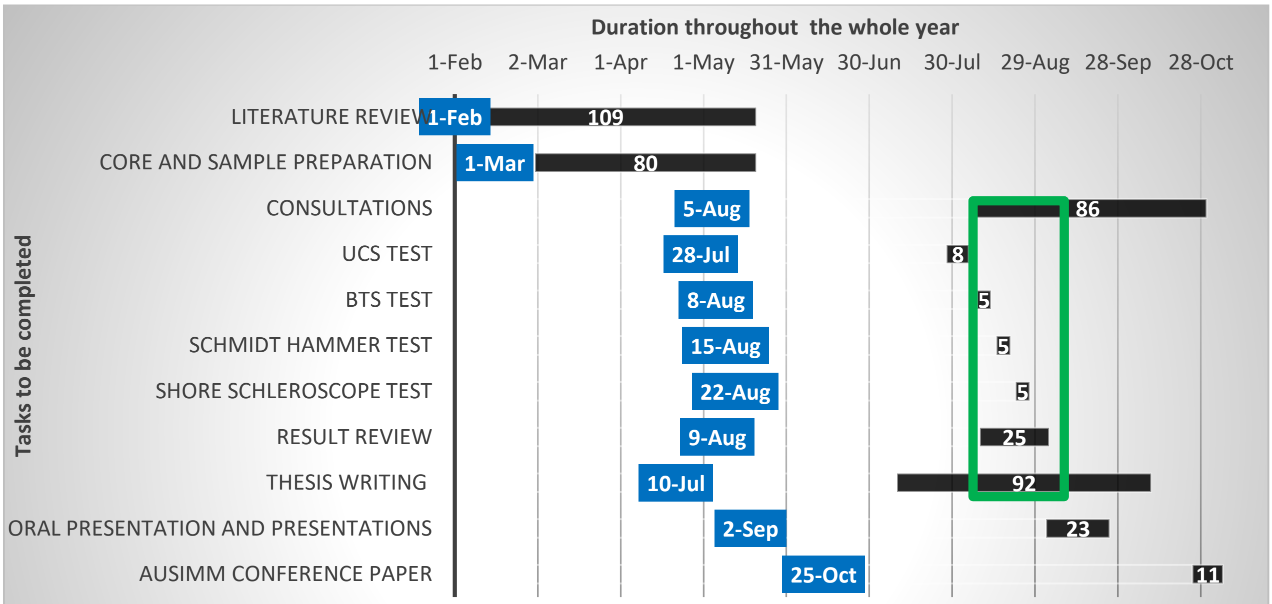
Table 11

Breakdown of the cost involved until completion of the project.

Sample Type	*Number of Samples*	*Sample Price ($50/sample)*	*Delivery Cost ($)*	*Testing Cost ($200/Hr)*	*Total ($)*
Sandstone	14	700	$800	1000	3400
Brisbane Tuff	9	450			
Basalt	9	450			

5.3 SCHEDULE

In order to briefly show and include all the activities which are needed for this project from the start to the end, a Gantt chart summarising them was created. Figure 6 shows the schedule detailing how this project will be run throughout the whole year to achieve the aims and the objectives set in this thesis. Among the tasks in the schedule include some of the tasks which have been already achieved and those intended to be achieved.



	AusIMM Conference Paper	Oral Presentation and Presentations	Thesis Writing	Result Review	Shore Schleroscope Test	Schmidt Hammer Test	BTS Test	UCS Test	Consultations	Core and Sample Preparation	Literature Review
Start Date	25-Oct	2-Sep	10-Jul	9-Aug	22-Aug	15-Aug	8-Aug	28-Jul	5-Aug	1-Mar	1-Feb
Duration	11	23	92	25	5	5	5	8	86	80	109

Figure 6. Task scheduled throughout the year.

As it can be seen in Figure 6 one of the area is marked with a green rectangle. As per any other projects, this is the period where everything about the projects are happening at the same time and time and project management are taken into consideration to make sure this period is not affected resulting in project delay or incompletion of it. This is why the testing will be happening with few days gape in between to reduce the overloading.

6. EXPERIMENTAL RESULTS

6.1 OVERVIEW

Three series of tests were conducted and the results obtained in each experimental test were used to derive all the formula and the parameters required to determine the rock strength using different methods. The rocks used in this experiment are the Brisbane Tuff, Sandstone and Basalt. The experiment consists of 14 samples of sandstone, 9 basalts and 9 Brisbane Tuff samples. The rock strength of the Brisbane Tuff is very important in this project as it is the current rock host of the Clem 7 Tunnel. Sandstone and basalt are also found in a wide range of underground and on ground activities. The three series of tests conducted were UCS, BTS and PL tests. All the results in terms of fracture initiations and propagations were valid based on ISRM standards.

6.2 UCS RESULTS

6.2.1 Sandstone Results

UCS test was conducted on four sandstone samples. The dimensions and other properties in line with the ISRM are summarised in Table 12

Table 12

Summary of dimensions and parameters for Sandstone UCS Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/S)*	*Failure Time (s)*	*Peak Load(kN)*	*UCS (MPa)*
1	80.23	33.44	2.40	0.8	285.104	28.48	32.43
2	80.49	31.37	2.57	0.8	315.112	31.50	40.75
3	80.45	31.51	2.55	0.8	392.056	39.19	50.25
4	80.70	31.35	2.57	0.8	403.108	40.29	52.20
Average	**80.47**	**31.92**	**2.52**	**0.8**	**348.85**	**34.86**	**43.91**

For better results in determining a UCS of a sample, ISRM suggests that the loading rate should be between 0.5 to 1MPa/s. It was found that the loading rate influences physical and mechanical properties such as UCS, elastic modulus, cohesion and internal friction of samples and on the fracture toughness. The loading rate is found to be proportional to the results obtained while conducting UCS Test. A number of tests have been conducted with a different loading rate on a same rock sample and different results have been obtained on loading displacements, peak load and times it took for a sample to fracture (Yang, 2015). Hence, the loading rate chosen for this study was 0.8kN/s which is within the suggested range by the ISRM.

As shown in Table 12 above, all the UCS tests conducted on each sample resulted in different values of time it took each sample before failure, peak load and UCS. The UCS values between the four samples ranged from 32.43MPa to 52.20 MPa. Hence an average of each parameter was determined and used to calculate the UCS value and it was found to be 43.91MPa. During the experiment, the data acquisition was used to record the axial deformation as the load was being applied constantly. It can be seen that the data of the experiment are only different by a small number between samples which shows that the samples used were almost the same in terms of their geological and physical properties. The data obtained were used to plot the stress versus strain which can be used to determine the Young's Modulus of this particular sandstone. Furthermore, a plot of UCS versus each sample was created to show the UCS value of each sample. These plots can be found in Figure 7 a) and b) respectively.

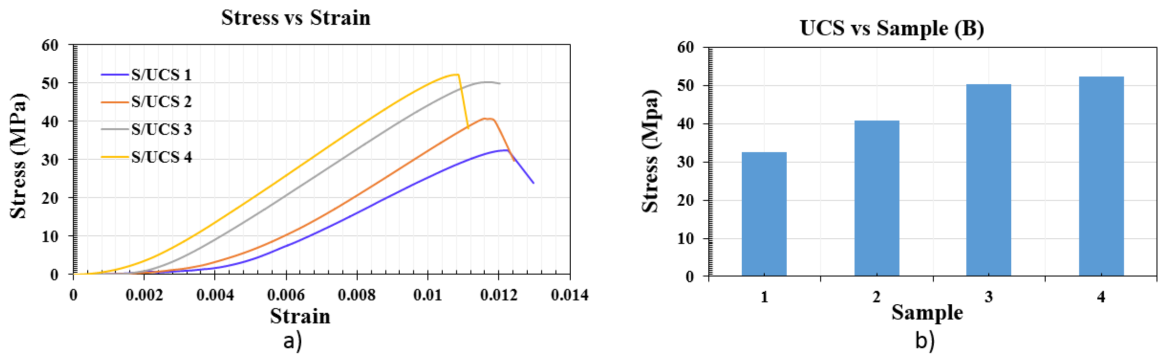


Figure 7. UCS test on sandstone for stress vs strain in a) and UCS vs Sample in b).

6.2.2 Brisbane Tuff Results.

The UCS test for Brisbane Tuff was conducted the same way as the sandstone samples. Dimensions and other properties in line with the ISRM is summarised used can be found in Table 13. There were 2 Brisbane Tuff samples used for this particular test.

Table 13

Summary of dimensions and parameters for Brisbane Tuff UCS Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/s)*	*Failure Time (s)*	*Peak Load(kN)*	*UCS (MPa)*
1	80.27	32.65	2.46	0.8	727.52	72.75	86.89
2	80.26	32.38	2.48	0.8	781.324	78.11	88.89
Average	80.26	31.92	2.47	0.8	754.42	75.43	87.63

The results obtained in the table above were averaged for final analysis. The peak load ranged between 72.75kN to 78.11 kN whereas their corresponding UCS was 86.89 and 88.89 MPa respectively. Although the aim of this experiment is to determine the correlation between the three different tests (UCS, BTS and PL), it should also be noted that the Brisbane Tuff had a higher peak load and the UCS compared to sandstone samples. These values also reflect to the time it took for each sample to fail. Using the data in the table above, plots of stress versus strain and UCS versus Sample were plotted to illustrate the results as it can be seen in Figure 8 a) and b) respectively.

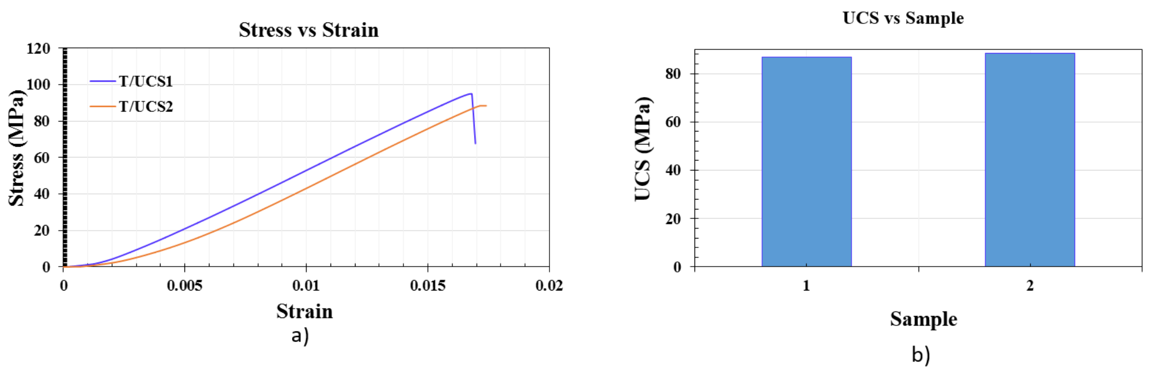


Figure 8. UCS test on Brisbane Tuff for stress vs strain in a) and UCS vs Sample in b).

6.2.3 Basalt Results

UCS test was conducted on two basalt samples. The dimensions and other properties in line with the ISRM is summarised in Table 14.

Table 14

Summary of dimensions and parameters for Basalt UCS Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/s)*	*Failure Time (s)*	*Peak Load(kN)*	*UCS (MPa)*
1	80.29	32.80	2.5	0.8	135	187.1	203
2	80.49	33.10	2.4	0.8	53	174.81	221
Average	80.39	32.95	2.45	0.8	94	180.95	212

The two samples used here have been averaged as well so that they can be used for the final analysis. The peak loads were found to be 174.81 and 187.10kN respectively whereas their respective UCS were 203 and 221MPa. The average of 212 MPa was deduced from the results. As it can be seen in the values obtained while conducting the UCS on basalts are higher than those obtained in both sandstone and Brisbane Tuff. This implies that basalt is the strongest sample among the three samples. Figure 9 shows the plot of stress versus strain in a) and UCS versus sample in b) respectively.

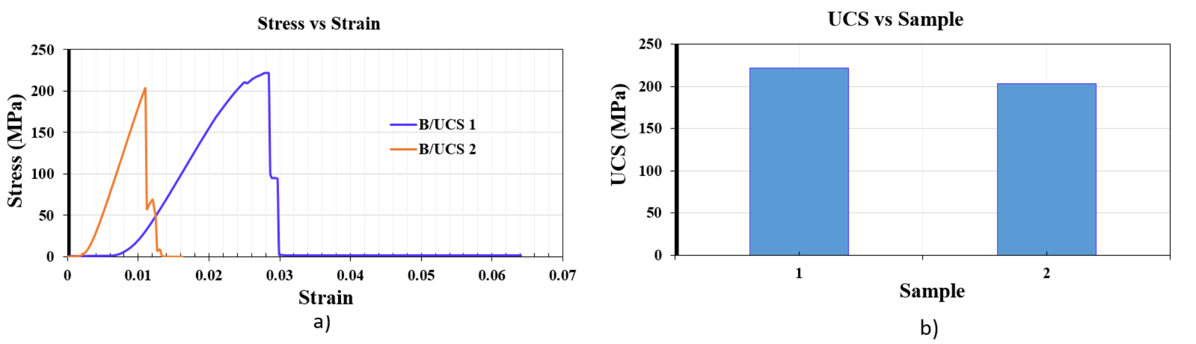


Figure 9. UCS test on Basalt for stress vs strain in a) and UCS vs Sample in b).

6.3 Brazilian Tensile Strength Results

6.3.1 Sandstone Results

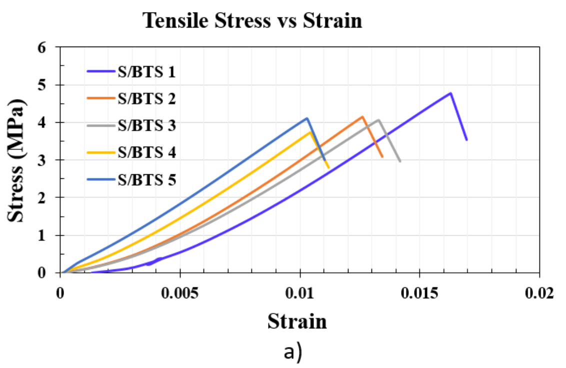
The BTS test was conducted on five sandstone samples. The dimensions and other properties in line with the ISRM is summarised in Table 15.

Table 15

Summary of dimensions and parameters for Sandstone BTS Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/S)*	*Failure Time (s)*	*Peak Load(kN)*	*Tensile Stress (MPa)*
1	26.70	52.16	1.95	0.8	104.502	10.44	4.77
2	26.82	52.14	1.94	0.8	91.302	9.12	4.15
3	26.76	52.17	1.94	0.8	88.9	8.87	4.04
4	26.97	52.18	1.93	0.8	82.802	8.27	3.74
5	27.05	52.29	1.93	0.8	91.002	9.09	4.09
Average	26.86	52.20	1.94	0.8	91.70	9.16	4.16

The results of the five samples used for BTS were averaged as shown in the table above. The tensile strength of each sandstone was determined and ranged from **3.74** to **4.77Mpa.** The average gave a value of **4.16Mpa**. These results were plotted to show the key values illustrating the results in the experiment. Figure 10 a) and b) shows the plots respectively.



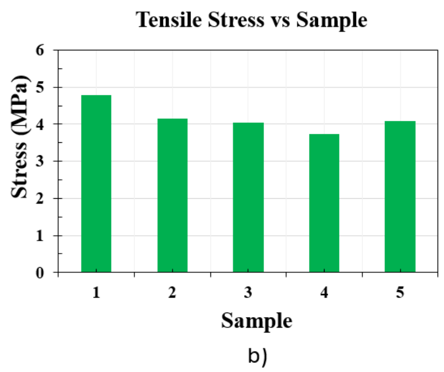


Figure 10. BTS test on Sandstones for tensile stress vs strain in a) and tensile stress vs Sample in b).

6.3.2 Brisbane Tuff Results

The BTS test was conducted on five Brisbane Tuff samples. The dimensions and other properties are in line with the ISRM. These results show the time it took each sample before it could fail, the loading rate and tensile stress of each sample. All the results are summarised in Table 16.

Table 16

Summary of dimensions and parameters for Brisbane Tuff BTS Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/s)*	*Failure Time (s)*	*Peak Load(kN)*	*Tensile Stress (MPa)*
1	26.92	51.99	1.93	0.8	198.408	20.02	9.11
2	26.63	51.96	1.95	0.8	179	18.27	8.41
3	26.77	51.93	1.94	0.8	186.002	18.85	8.63
4	26.68	51.94	1.95	0.8	167.50	16.90	7.76
5	26.74	51.91	1.94	0.8	163.906	16.43	7.54
Average	26.75	51.95	1.94	0.8	178.96	18.10	8.29

The same procedure was followed by averaging the results of the five samples which ranged from 7.54MPa to 9.11MPa for the tensile strength of the Brisbane Tuff and the average was 8.29MPa. Using the value in the table above, plots of tensile vs strain and tensile versus samples were created and the can be found in Figure 11 a) and b).

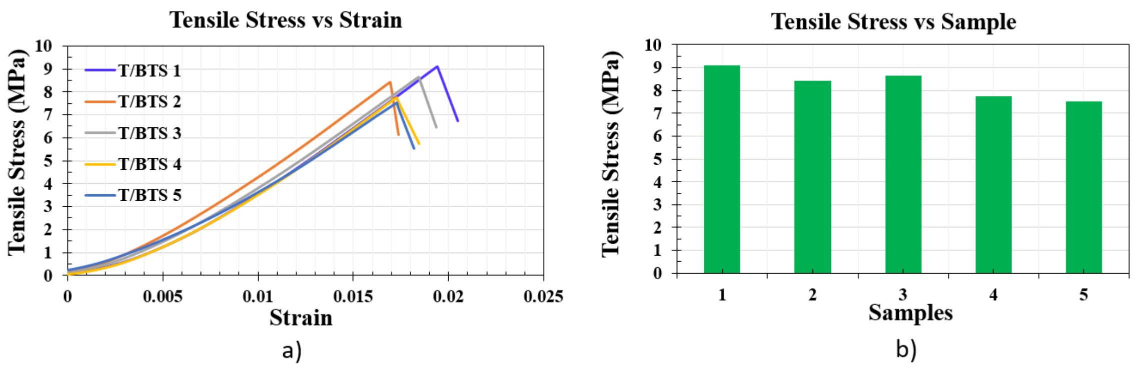


Figure 11. BTS test on Brisbane Tuffs for Tensile stress vs strain in a) and Tensile Stress vs Sample in b)

6.3.3 Basalt Results

The BTS test was conducted on three basalt samples. The dimensions and other properties in line with the ISRM is summarised in Table 17.

Table 17

Summary of dimensions and parameters for Basalt BTS Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/S)*	*Failure Time (s)*	*Peak Load(kN)*	*Tensile Stress (MPa)*
1	27.40	51.87	1.89	0.8	328.306	33.00	14.78
2	27.40	51.87	1.89	0.8	334.61	33.52	15.35
3	26.80	51.88	1.93	0.8	250.00	27.68	12.39
Average	27.20	51.87	1.94	0.8	304.305	31.40	14.17

Three samples were tested individually and averaged to compare their values with the other methods on the same type of the rocks. The peak load at failure ranged from 27.68 to 33.52MPa while the Tensile Stress ranged from 12.39 to 15.35MPa respectively. The tensile stress average was found to be 14.17MPa.

For analysis purpose, a fourth sample was not considered due to the discrepancy in the value obtained from its test compared to the other samples which implies that it would result in giving a wrong conversion factor. The peak load was only 5kN and it took the sample 57 seconds to fail giving a tensile strength of 2.24MPa. These results could be due to a number of reasons such as defects in the sample, some discontinuities and other geological properties which are not in the scope of this thesis. The results of the three samples are plotted in Figure 12 a) and b) respectively.

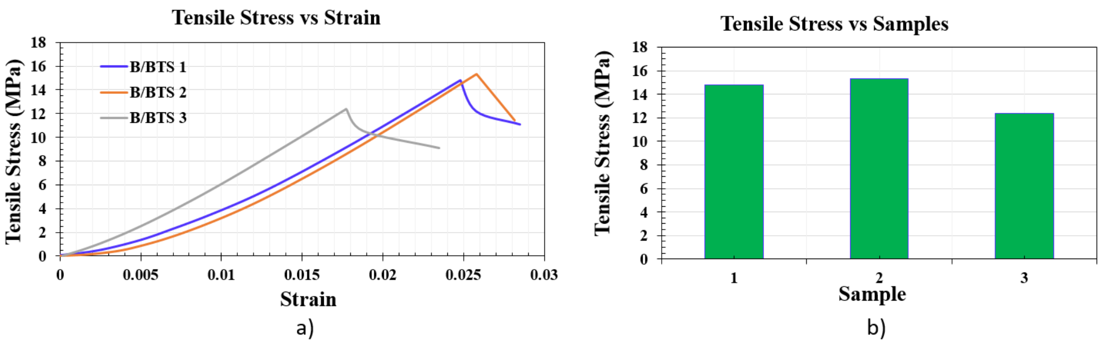


Figure 12. BTS test on Basalts for Tensile stress vs strain in a) and Tensile Stress vs Sample in b).

6.4 POINT LOAD INDEX RESULTS

6.4.1 Sandstone Results

The PL test was conducted on five sandstone samples. The dimensions and other properties in line with the ISRM is summarised in Table 18.

Table 18

Summary of dimensions and parameters for Sandstone PL Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/s)*	*Failure Time (s)*	*Peak Load(kN)*	*Pl Index (MPa)*
1	61.6	52.22	1.18	0.8	5	6.15	2.30
2	61.18	52.14	1.17	0.8	6	7.65	2.87
3	61.28	52.18	1.17	0.8	5	5.95	2.23
4	61.28	52.15	1.17	0.8	6	7.08	2.65
5	61.15	52.16	1.17	0.8	7	7.81	2.93
Average	**26.75**	**51.95**	**1.17**	**0.8**	**5.8**	**6.93**	**2.59**

As per other samples, five samples of sandstone were used and each sample was tested and provided the peak load which was used to calculate the point load index. The peak load ranged from 5.95 to 7.81kN and from 2.23 to 2.93MPa for the point load index. All the values obtained were then averaged in order to be used for the general analysis. Peak load and the point load index are 6.93kN and 2.59MPa respectively. Figure 13 shows the plot of point load index versus sample with the estimated value as described above. The peak load versus sample plot can be found in Appendix 3.

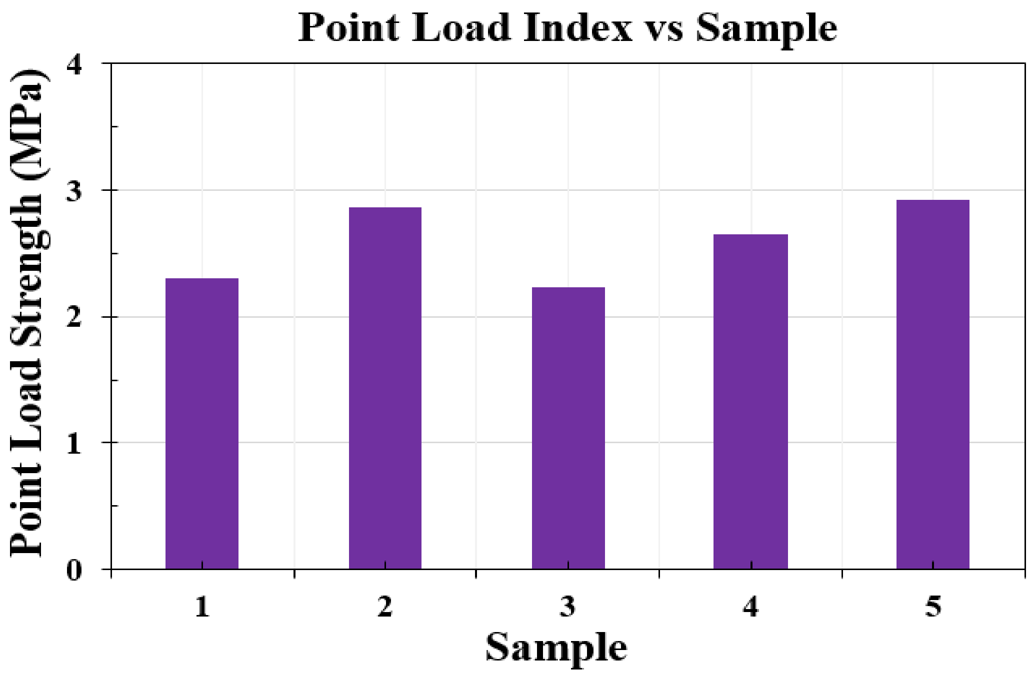


Figure 13. Point Load Index vs strain results for Sandstone.

6.4.2 Brisbane Tuff Results

The PL test was conducted on two Brisbane Tuff samples. The dimensions and other properties in line with the ISRM are summarised in Table 19

Table 19

Summary of dimensions and parameters for Brisbane Tuff PL Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/s)*	*Failure Time (s)*	*Peak Load(kN)*	*Pl Index (MPa)*
1	62.32	51.86	1.20	0.8	6	9.54	3.61
2	62.30	51.91	1.20	0.8	7	8.45	3.19
Average	26.75	51.95	1.17	0.8	5.8	6.93	3.40

For the Brisbane Tuff, only two samples were used. Each was tested and the results are shown in the table above. Again, the peak load of each sample was used to calculate the point load index. The peak road and the point load index ranged from 8.45 to 9.54kN and 3.19 to 3.61MPa respectively. For further general analysis, these values were then averaged and they were found to be 6.93kN for the peak load and 3.40MPa for the point load index. Figure 14 shows the plot of point load index as described above. The peak load versus sample plot can be found in Appendix 3.

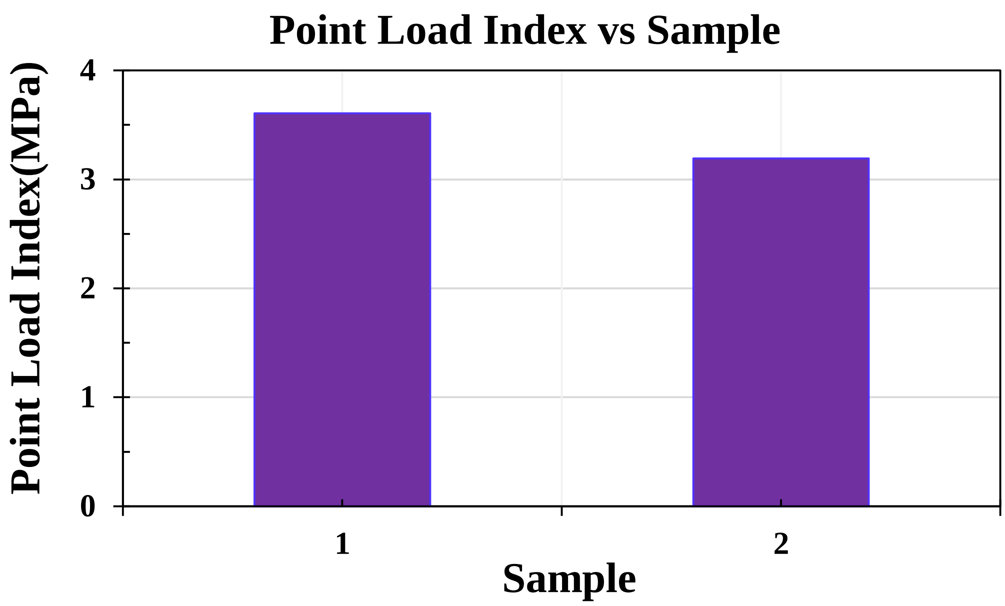


Figure 14. Point Load Index vs strain results for Brisbane Tuff.

6.4.3 Basalt Results

The PLI test was conducted on four basalt samples. The dimensions and other properties in line with the ISRM are summarised in Table 20.

Table 20

Summary of dimensions and parameters for Basalt PL Testing.

Sample	*Length (mm)*	*Diameter (mm)*	*L/D*	*Loading Rate (kN/s)*	*Failure Time (s)*	*Peak Load(kN)*	*PI Index (MPa)*
1	60.52	51.79	1.20	0.8	7	14.58	5.52
2	63.37	51.85	1.22	0.8	9	18.32	6.93
3	63.11	51.91	1.21	0.8	10	16.78	6.33
4	63.42	51.81	1.22	0.8	11	19.30	7.31
Average	**62.61**	**51.84**	**1.21**	**0.8**	**9.25**	**17.25**	**6.52**

Four samples of basalt rocks were tested and each value obtained during the experiment is summarised in the table above. The peak load ranged from 14.58 to 19.30MPa whereas the point load index values ranged from 5.52 to 7.31MPa respectively. For further analysis, an average was calculated. The average peak load was found to be 17.25 MPa and the point load index average is 6.52MPa.

A fifth sample was tested but resulted in data which showed lack of correlation with the other four samples. The peak load was only 7.43kN and it took the sample 4 seconds to fail giving a point load index of 2.81MPa. These results could be due to a number of reasons such as defects in the sample, some discontinuities and other geological properties. The results of the four samples are plotted in Figure 15 whereas the plot for the peak load versus sample plot for basalt can be found in Appendix 3.

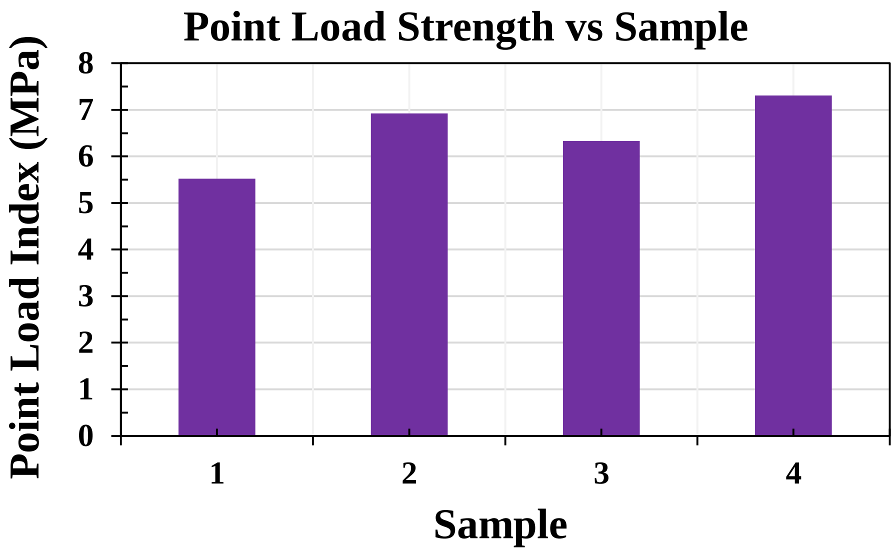


Figure 15. Point Load Index vs strain results for Basalt.

7. RESULTS DISCUSSION

7.1 OVERVIEW

The results were collected from all the three different samples and all types of tests conducted to compare between them and the past findings as well as concluding the results obtained specifically for the samples used in this experiment. As stated before, the main aim is to determine the *k factor* between UCS, BTS and PL which is specific for Sandstone, Brisbane Tuff and Basalt. In order to conduct the analysis, past findings where used to check if they were valid for these types of rocks. When conducting analysis, there are a number of things which can be looked at especially for an experimental study. These can be the effect of some of the parameters such as the change in diameter, loading rate, water content, discontinuities and other geological features. However, for this report many of these were made as part of the assumptions. The loading rate was constant for the samples, diameter was in line with ISRM and where it was found different, the equivalent diameter was used.

7.2 ESTABLISHMENT OF CORRELATION

In order to correlate the experimental findings in the three tests conducted, a schematic relationship was created and used to show the existing relationship between each test by previous researchers and how the three tests can relate. The aim of this approach was to show that past researches have worked on similar subjects but their results were different in each case. Furthermore, some of the values and the correlation found were based on different rock types, hence the need to carry this experiment on sandstone, Brisbane Tuff and basalt which were not discussed in past findings. The other reason for this approach was to prove whether the *k factor* is applicable to all the rock types or if it only applies to particular rocks. Figure 10 shows the approach used to determine the k factor between the different tests and rocks. As it can be seen, some correlations have been established for PL into UCS and BTS into UCS.

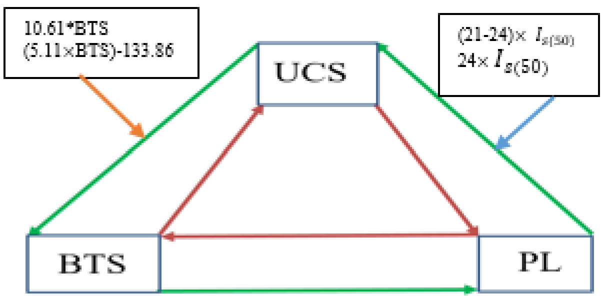


Figure 16. Schematic approach to correlate PL and UCS, UCS and BTS and BTS with PLI.

Given that there were three different samples, this approach looked at each rock sample individually. As stated in Section 2.2.2 and 2.2.3, a number of researches have been done and k factor between UCS and PL as well as UCS and BTS was determined. In that section, findings show that *k factor* values of 21-24 are commonly used to convert the PL Index into UCS or simply factor 24. Other researches in the same section show that these *k factors* vary from rock to rock. From the previous researches, it was stated that the following formula is commonly used to convert the PL into UCS:

$$(21 - 24) \times \ I_{s(50)} \tag{5)}$$

The calculation of the point load index $I_{s(50)}$ was explained in Section 4.3.2 in Equation 4). However, the question remains whether this is a general *k factor* for all type of rocks. Table 21 shows the summary of all the data used to calculate the k factor for the three samples and the values obtained in order to convert the PL index into UCS.

Table 21

Experimental data to convert PL into UCS.

Rock Type	*UCS (MPa)*	$I_{s(50)}$ *(MPa)*	*K Factor*	*K Factor Range*
Sandstone	43.91	2.47	17.78	14-17
Brisbane Tuff	87.63	3.40	25.78	24-27
Basalt	212	6.5	32.62	31-40

As it can be seen in Table 21, the *k factors* found from the experimental data in order to convert the point load index into the UCS values are different to the previous *k factors* from previous researchers. Although the main purpose was not to find out the strongest rocks in the three samples, it can be noticed that the results were consistent and met the expectations in regards to their rock strengths. Sandstone was weaker followed by the Brisbane Tuff and Basalt found to be the strongest. The consistency comes in the fact that in all the three different tests conducted, the value obtained in each sample ranged in the same chronological strength from sandstone to basalt as expected. It can also be seen that there is a trend between the *k factor* of a rock and its strength. The higher the UCS the bigger the conversion factors. In addition to that, the conversion between the UCS and the BTS was conducted the same way as for the point load index into UCS by analysing the values obtained from the experiment and look at the difference between the two tests. The data obtained in the experiment to convert the BTS into UCS are summarised in Table 22.

Table 22

Experimental data to convert BTS into UCS.

Rock Type	*UCS (MPa)*	*BTS (MPa)*	*k Factor*	*k Factor Range*
Sandstone	43.91	4.16	10.55	8-12
Brisbane Tuff	87.63	8.23	10.65	9-11
Basalt	212	14	15.14	14-17

From the previous research data, the *k factors* found to convert BTS into UCS seemed to be fluctuating. However, the use of UCS being 10 times the tensile strength of the rock is still practical in many areas. From the experimental data, it can be seen that some of the *k factors* are not by far different with the previous *k factors*. In fact, Brisbane Tuff and Sandstone had approximately the same *k factor* of 10 times the tensile strength as the one determined in 2012 by Kahraman *et al* which was determined from different rock types including limestone.

There have been no so many researches which relate the BTS and PL. Once the correlation between BTS and UCS as well as the one between PLI and UCS are established it is easy to determine the relationship between BTS and PLI. However, there is practically no need to determine this as the two methods are relatively easier to use compared to UCS test. Therefore, the main focus is to find alternatives for UCS by using BTS or PL tests. This is due to the fact that both BTS and PL are the easiest ones to use, flexible and cheaper compared to determining the rock strength by UCS tests. Furthermore, once the correlation between UCS and both BTS and PL has been determined, it is easier to determine the correlation between BTS and PL using the same data obtained from the experiment or by solving simultaneous equations to give numerical values. In this experiment, the tensile strength and the point load index were close in values that they only differed by a factor of 1.7 to 2.15.

7.3 Summary of Findings

Table 23 is presented and all the value are shown in red for the conversion *k factors* from PL index to UCS and BTS to UCS. This table shows the k factors obtained from PLI into UCS as well as those found from BTS into UCS. An approximate values of k factors for sandstone and Brisbane Tuff is observed in the table for the conversion of the BTS tests into UCS. These values match with the previous k factor established by Kahraman *et al* (2012). The table has also k factor and k factor range values. The k factor ranges were obtained by conducting various iterations of all possible combinations between the values found from the smallest value to the highest value in order to find the best possible lower and upper boundary of the range. The single k factor on the other hand involved the simple division between the values of two different tests conducted.

Table 23

Summary of all the k factors for all the samples and tests.

Rock Type	*UCS (MPa)*	$I_{s(50)}$ *(MPa)*	*K Factor*	*K Factor Range*	*BTS (MPa)*	*K Factor*	*K Factor Range*
Sandstone	43.91	2.47	17.78	14-17	4.16	10.55	8-12
Brisbane Tuff	87.63	3.40	25.78	24-27	8.23	10.65	9-11
Basalt	212	6.5	32.62	31-40	14	15.14	14-17

8. CONCLUSION

The determination of k factor between both BTS and PLI in order to convert them into UCS is a process which requires an extensive study on different samples. Researches have been conducted and few correlations have already been established. However, the use of these factors remains a question as to whether the previous findings should be generalised and be used on every rock sample. Based on the findings from this experiment, it can be concluded that any k factor from this experiment or the previous findings should only be used on specific rocks and more importantly on same rock samples. Hence all the calculations should refer to the appropriate conversion factors, applicable to the rocks involved. The corresponding conversion factors of the three samples were determined as planned. The samples and the dimensions were all prepared in line with the International Society of Rock Mechanics (ISRM) standards to consider the reputability and reliability of the experiment.

The results obtained from this study were that Sandstone k factor is 17.78 to convert from PL Index to UCS. That is UCS is 17.78 times the Point Load Index of that particular sandstone. The k factor between UCS and BTS was that UCS is 10.55 times the Brazilian Tensile Strength for the same sandstone. The Brisbane Tuff k factor was 25.78 times point load index to convert PL into UCS and 10.65 times the Brazilian Tensile Strength. As for Basalt which was found to be the strongest rock the k factor for UCS and PL was that UCS is 32.62 times the Point Load Index while it was found to be 15.14 times the Brazilian Tensile Strength.

As it can be seen in the values of k factors obtained, it can be concluded that although Sandstone and Brisbane Tuff are two different rocks, their conversion factor is approximately the same is around 10 times the tensile strength and point load index. Furthermore, there is a correlation between the strength of the rock and the k factor. The stronger the rock the higher the conversion factor. In addition to that, it should also be noted that the conversion factor which is usually used to convert PLI into UCS should take into account different rock types which fall into the same factor otherwise, some calculations will be overestimating or underestimating their UCS. Furthermore, future works are still needed to be done. The results of an experimental analysis in rock mechanics depend on a lot of things. Core samples, locations, homogeneity or inhomogeneity, in-situ strength, initial cracks or defects and other geological properties can affect the results which can lead to a misleading conclusion. Hence, more tests on different rock samples should be conducted to ensure data on the findings, the results and the type of rock tested are available in abundance so that the estimation of the UCS is as accurate as possible.

9. RECOMMENDATIONS

Based on how the experiment was conducted and the type of tests involved, a number of recommendations need to be implemented to improve the accuracy and the credibility of the findings. The results of an experimental analysis in rock mechanics depend on a lot of things. Core samples, locations, homogeneity or inhomogeneity, in-situ strength, initial cracks or defects and other geological properties can affect the results which can lead to a misleading conclusion. In order to improve and get the best results which can achieve the aims set up in the experiment, a few things need to be addressed:

- samples that are used for different tests should have similar properties and come from the same core and same locations;

- use as many as samples on each test as possible to get enough data and increase the regression and the accuracy in the data;

- given the fact that the correlation was found to be varying in different rocks, these type of tests should be done on many different rocks and have an archive or data log of these findings for future reference;

- conduct the test on different size scale and different configuration to explore other useful parameters;

- conduct numerical modelling and compare the results with experimental to increase confidence in the findings;

- use triaxial loading on samples; and

- conduct test on different temperatures.

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APPENDICES

APPENDIX 1 CORRELATIONS BY OTHER RESEARCHERS ON LIMESTONE

Table 24

Laboratory Tests results and Predicted UCS (Nazir *et al*, 2013).

No	Sample Type	Determined BTS (MPa)	Determined UCS (MPa)	Predicted UCS (MPa) Kahraman et al.(2012)	Predicted UCS (MPa) Altindag and Guney (2010)	Predicted UCS (MPa) Farah (2011)
1	Limestone	7.78	70.56	82.55	111.11	38.83
2	Limestone	6.54	52.67	69.39	92.23	32.50
3	Limestone	3.02	21.18	32.04	40.27	14.51
4	Limestone	5.93	61.61	62.92	83.04	29.38
5	Limestone	5.78	51.73	61.33	80.79	28.61
6	Limestone	3.22	27.29	34.16	43.14	15.53
7	Limestone	4.98	52.20	52.84	68.86	24.52
8	Limestone	8.83	78.09	93.69	127.27	44.20
9	Limestone	6.90	53.14	73.21	97.69	34.34
10	Limestone	8.28	60.20	87.85	118.79	41.39
11	Limestone	10.36	83.26	109.92	151.06	52.02
12	Limestone	7.41	76.67	78.62	105.46	36.94
13	Limestone	7.29	58.5	77.35	103.62	36.33
14	Limestone	11.09	85.62	117.66	162.51	55.75
15	Limestone	6.2	54.6	65.78	87.10	30.76
16	Limestone	14.2	100.7	150.66	211.84	71.64
17	Limestone	5.4	42.3	57.29	75.11	26.67
18	Limestone	6.1	51.7	64.72	85.60	30.25
19	Limestone	7.5	60.4	79.58	106.83	37.40
20	Limestone	6.3	50.3	66.84	88.61	31.27

APPENDIX 2 PHOTOS OF SAMPLES USED IN THE EXPERIMENT

Figure 17. Sandstone samples UCS Test in A and B before and after respectively.

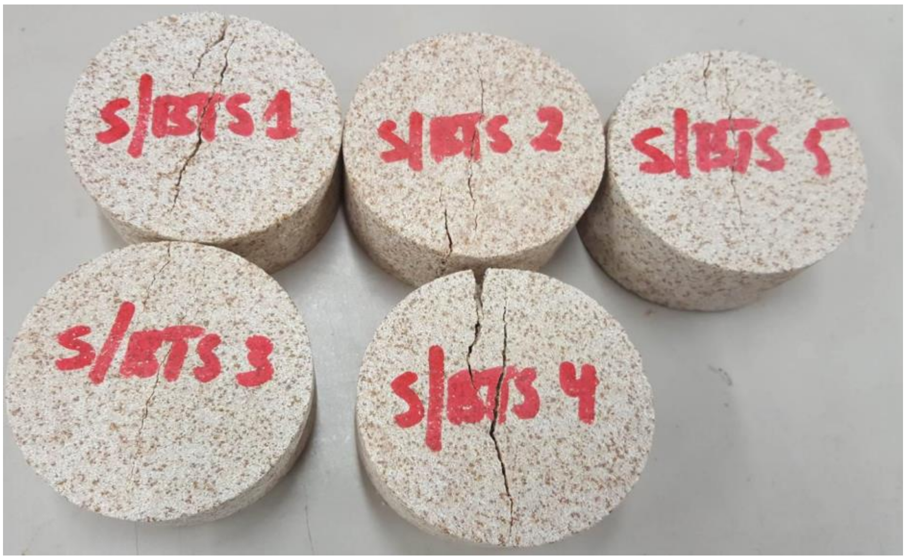

Figure 18. Sandstone Samples after BTS test.

Figure 19. Basalt samples after BTS Test.

Figure 20. Brisbane Tuff Samples after BTS Test.

Figure 21. Basalt sample after Point Load Test.

Figure 22. Sandstone Sample after Point Load Test.

APPENDIX 3 PLOTTED GRAPHS FOR SOME OF THE RESULTS FROM EXPERIMENT

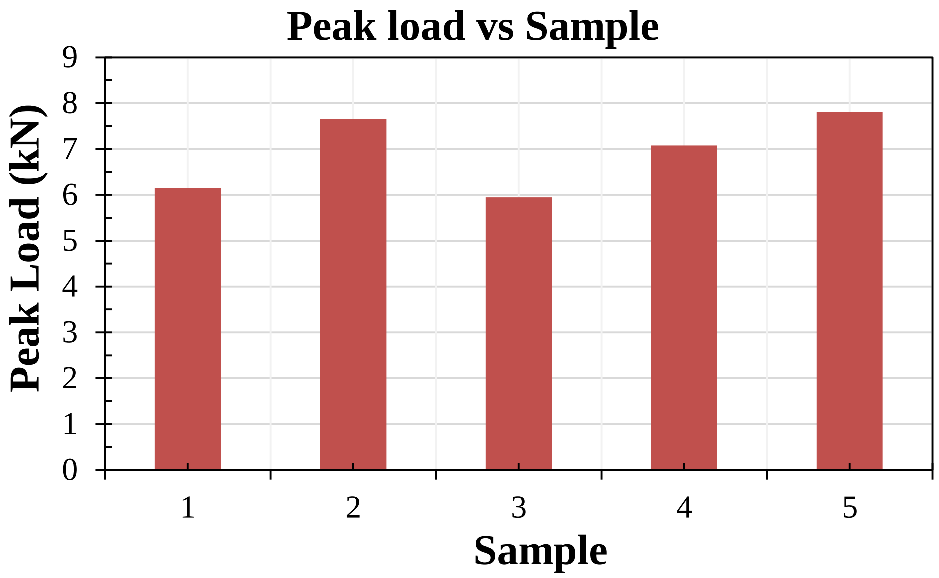

Figure 23. Peak Load vs strain results for Sandstone PL Test

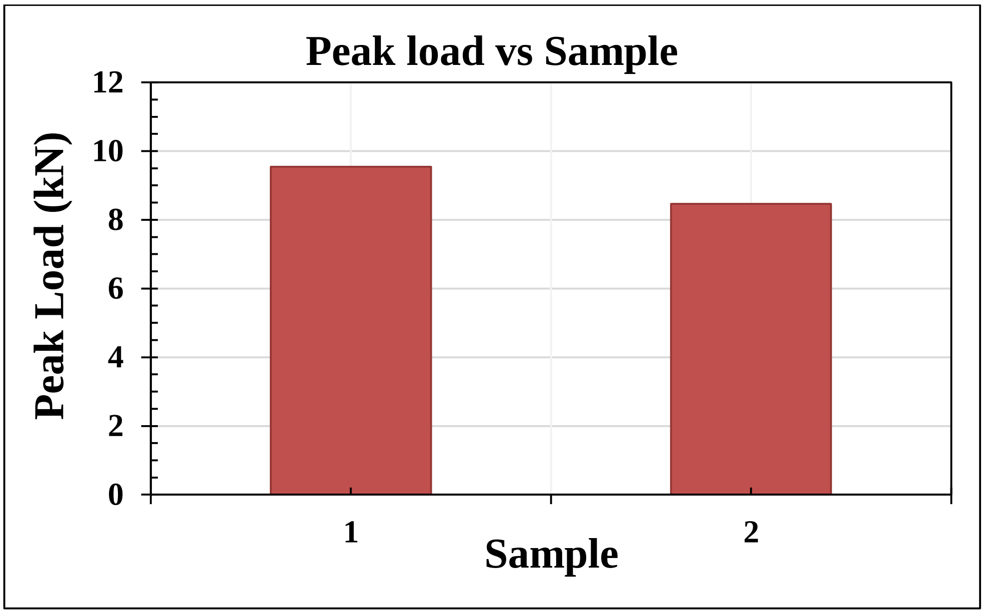

Figure 24. Peak Load vs strain results for Brisbane Tuff PL Test

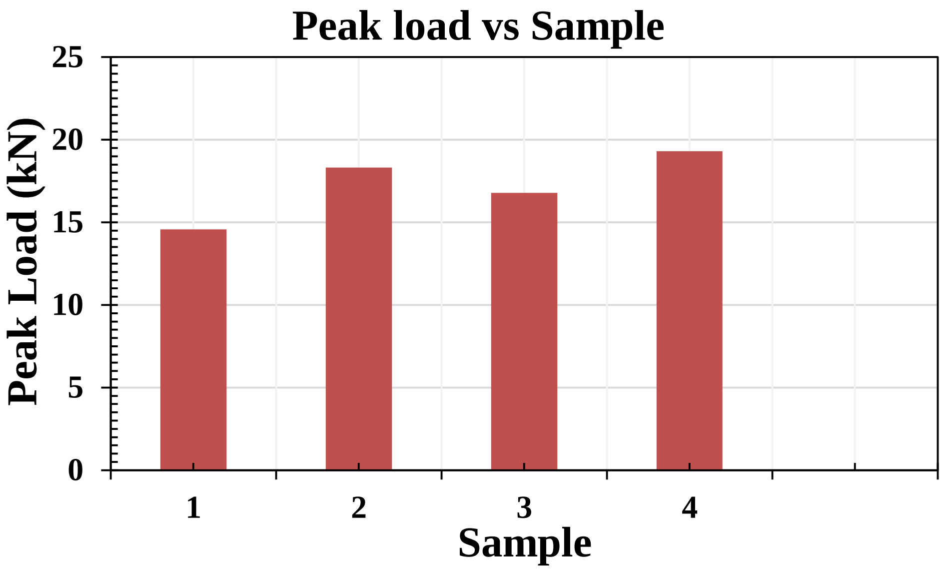

Figure 25. Peak Load vs strain results for Brisbane Basalt